Direct Initiation of Acetylene-Oxygen Mixture Using Laser Ablation

Hidefumi Kataoka[1], Hiroyuki Kato[1], Kazuhiro Ishii[1]

[1]Department of Mechanical Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

1 Introduction

Recently propulsion systems using detonation have been intensively studied because of their simple construction and high thermal efficiency. In terms of initiation of detonation in a engine combustor, direct initiation is desirable, although it requires a relatively large amount of energy to generate a strong blast wave causing detonation. A laser is a probable candidate for the energy source of direct initiation, since it can provide high energy density in a very short time without perturbing a flow field. In particular, laser ablation is expected to achieve the direct initiation with a smaller amount of energy as compared to laser breakdown [1, 2].

In the present work, experiments were performed to study the critical energy of direct initiation using laser ablation.

2 Experimental apparatus

The arrangement of the experimental apparatus is shown schematically in Fig.1. The laser was a pulsed Q-switched Nd:YAG laser(LOTIS TII, LS2137U/2), operating at a wavelength of 532 nm, with a pulse duration of 8 ns and a beam diameter of 8 mm. The laser energy E_0 was varied from 1 to 200 mJ using a combination of a 1/2 wave plate and a polarizing beam splitter and was monitored by a laser power detector (OPHIR, PE50BB). The laser beam was focused by a lens with focal length of 60 mm in the cylindrical combustion chamber 30 mm in diameter and 40 mm in length. A target used as ablation material was fixed to the stainless steel disk, which is opposed to an optical window installed in the combustion chamber for laser transmission. Soot was coated on the end wall of the combustion chamber for recording the cellular structure, while a pressure transducer (PCB, 113A22) was placed at the other end wall.

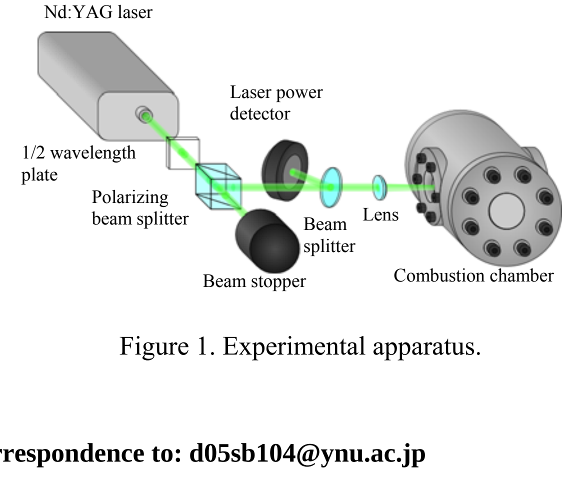

Figure 1. Experimental apparatus.

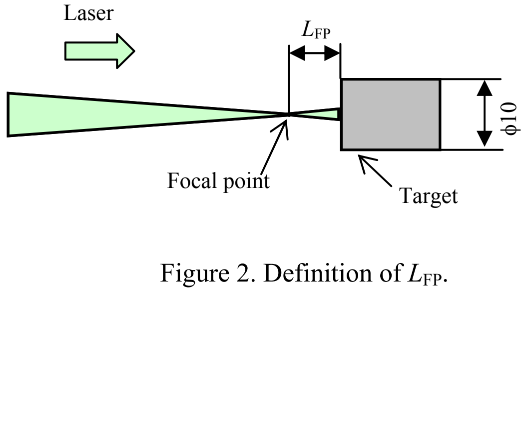

Figure 2. Definition of L_{FP}.

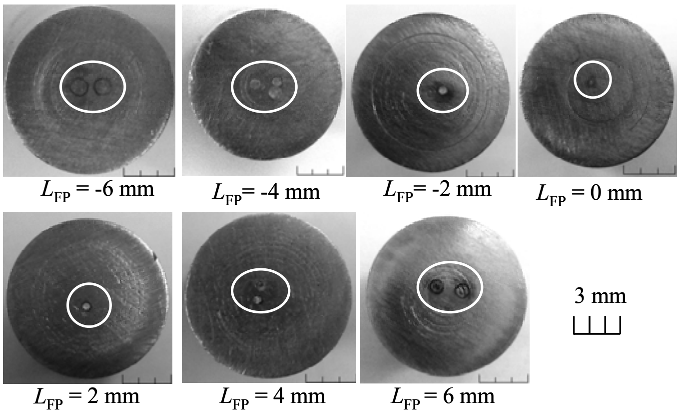

Figure 3. Surface of the target.

In the present work, relative focus position of the laser beam to the target was changed to study optimal layout of the optical components. The distance between the focal point of the laser beam and the target surface, L_{FP} was ranged from -6 mm to 6 mm, as shown in Fig. 2. The target was a stainless steel rod 10 mm in diameter. A stoichiometric acetylene-oxygen mixture was introduced into the combustion chamber under an initial pressure of 50 kPa and a room temperature. Success of direct initiation was confirmed by both pressure histories and appearance of cellular structure on the soot record.

3 Results and discussion

The surface condition of the target after tests is shown Fig. 3. Erosion caused by the laser ablation can be found in all the photographs. Several marks of erosion were made because the position of the laser bean spot was changed after several tests on the same target surface to avoid effects of the surface damage on the ablation process. Figure 4 shows typical pressure histories for L_{FP} = 0 mm. In the case of E_0 = 57 mJ, several pressure peaks larger than the CJ pressure indicate successful direct initiation of detonation. Reduction of the laser energy to 39 mJ gives a gradual pressure increase reaching finally to the combustion pressure at constant volume P_{ISO}, which shows the failure case of direct initiation.

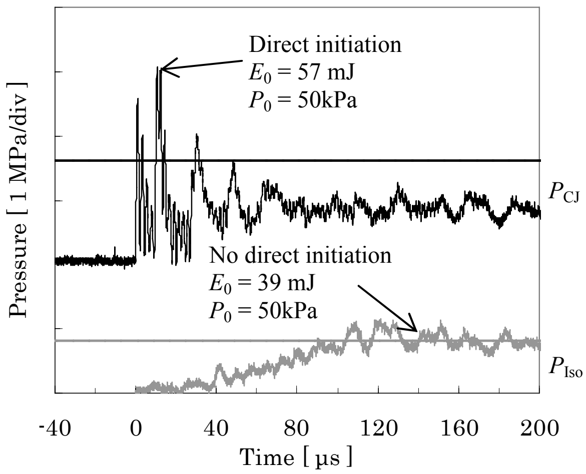

Figure 4. Pressure histories. L_{FP} = 0 mm. P_{CJ} and P_{Iso} denote the CJ pressure and combustion pressure at constant volume condition, respectively.

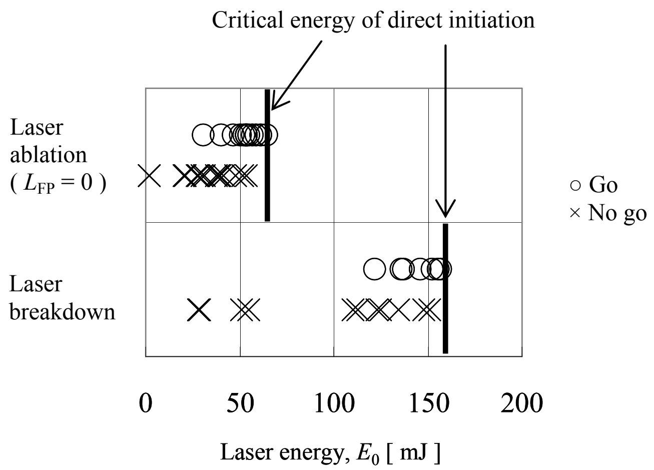

Figure 5. Comparison of critical energy between laser ablation and laser breakdown.

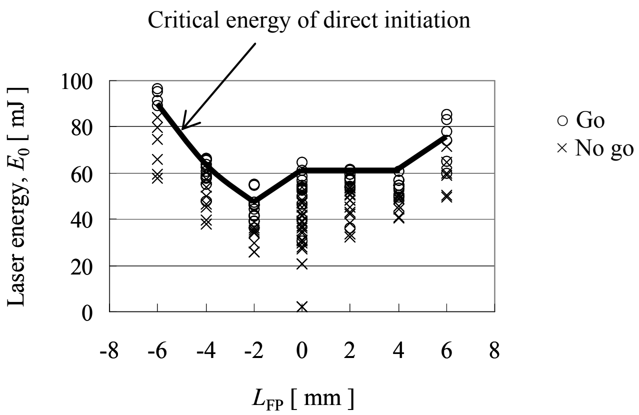

Figure 6. Effects of the distance between the target surface and the focal point, L_{FP} on critical energy of direct initiation.

The critical energy of detonation for laser ablation and laser breakdown is shown in Fig. 5. Open circle shows success of direct initiation and cross symbol failure. The solid line means the critical energy with which direct initiation of detonation can be assured. For comparison tests of laser breakdown were also conducted by replacing the stainless steel disk supporting the target by a glass window so that the laser beam could be transmitted without reflection. The laser ablation obviously needs less energy for direct initiation than the laser breakdown.

The critical energy of direct initiation, E_{CR} can be estimated by the following equation [2]

$$E_{CR} = \left(\frac{2197}{16}\right)\pi\rho_0 I_1 D_{CJ}^2 \lambda^3 \,, \tag{1}$$

where ρ_0 is density of the mixture, I_1 is 0.6 for ratio of specific heats of 1.3 in the present case, D_{CJ} is CJ velocity, and λ is cell width [3]. This E_{CR} is essentially the energy to generate a spherical blast wave causing detonation. As for laser ablation, a hemispherical blast wave is formed by presence of the target surface. E_{CR} for laser ablation, therefore, is estimated to be a half of the critical energy calculated by Eq. 1. Such obtained E_{CR} is 35 mJ, which differs from the critical energy of 60 mJ shown in Fig. 5. This discrepancy is mainly because the whole laser energy is not contributed to generation of a blast wave owing to reflection of the laser on the target surface.

Figure 6 shows effects of the distance between the target surface and the focal point on the critical energy of direct initiation. In the range of -6 mm ≤ L_{FP} ≤ -2 mm, the critical energy decreases with increase in L_{FP}. This result is consistent with ignition characteristics of combustible mixtures using laser ablation [4]. However, the critical energy is found to be almost constant for 0 mm ≤ L_{FP} ≤ 4mm. Bach et al. have reported that the position of the target relative to the focal point had no influence on the spark energy, when the target was placed on the same optical axis as the laser beam, with the tip a few millimeters behind the focal point [1]. When L_{FP} is positive, breakdown of the mixture occurs near the focal point in addition to ablation of the target material. The interaction of blast waves generated by both the breakdown and ablation may account for the constant critical energy. Further increase in L_{FP} causes separation of the blast waves resulting increase in the critical energy.

4 Summary

The critical energy of direct initiation using laser ablation of an acetylene-oxygen mixture was experimentally studied with various distances between the focal point of the laser beam and the target surface. The critical energy in laser ablation is smaller than that in laser breakdown and has a complex dependence on the distance between surface of the target and the focal point.

References

[1] Bach GG et al. (1969). Direct initiation of spherical detonation in gaseous explosives. Proc. Combust. Inst. 12: 853.

[2] Lee JHS. (1984). Dynamic parameters of gaseous detonations. Ann. Rev. Fluid Mech. 16: 311.

[3] Manzhalei VI et al. (1974). Measurement of inhomogeneities of a detonation front in gas mixtures at elevated pressures. Combust. Explos. Shock Waves 10: 89.

[4] Mori K et al. (2003). Ignition characteristics of GH_2/GO_x mixture using laser ablation ignition. Trans. Jpn. Soc. Aero. Space Sci. 46: 121.